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# BEARING BRONZES WITH ADDITIONS OF ZINC, PHOSPHORUS, NICKEL, AND ANTIMONY

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## ABSTRACT

A study was made of copper-tin-lead-bearing bronzes with and without additions of zinc, phosphorus, nickel, and antimony. Tests made included wear resistance, resistance to impact, Brinell hardness, and resistance to repeated pounding at several temperatures.

In general, the alloys with 4 per cent zinc and the alloys with 0.05 per cent phosphorus gave superior results in the tests as compared with the alloys with nickel and antimony. The alloys with 2 per cent nickel showed decreased wear resistance but increased resistance to pounding, and the alloys with 1 per cent antimony gave low resistance to impact, otherwise these additions were favorable from the standpoint of the other tests.

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## I. INTRODUCTION

At the present time there are many specifications for bearing bronzes of the copper-tin-lead type which differ mainly in the amounts of other elements contained. The need for most of these specifications may be questioned, when it is considered that the tin and lead contents of these alloys are usually within the range of 0 to 15 per cent and 0 to 30 per cent, respectively. As a large number of bronze alloys having different compositions are used under similar conditions of service, it appears that there is little agreement as to the proper bronze compositions for given service conditions. For example, automotive engineers have diversified opinions as to the most suitable material for wrist-pin bushings. Some specify an alloy with a lead content not to exceed 1 per cent; others indicate that their choice is a material of 10 per cent lead, while still others are of the opinion that wrist-pin bearings should contain from 15 to 20 per cent lead.

In some specifications lead and zinc are classed as impurities, while in others of a similar nature they are listed as essential constituents. Some of the present specifications for bronze-bearing metals are given in Table 1.

In a previous bureau publication<sup>4</sup> the mechanical properties and the testing technique used in determining wear were reported upon for the copper-tin-lead alloys used in railroad equipment. The alloys contained slight amounts of common impurities. In a later bureau publication<sup>5</sup> on bronze bearings the alloys were made from commercially pure materials. It is uneconomical for bearing metals to be made wholly from new or "virgin" metals. The high value of copper, tin, and lead makes the reclamation of unserviceable bearings desirable. These "secondary metals" vary not only in the proportions of copper, tin, and lead, but also in amounts of various other elements, such as zinc, phosphorus, antimony, nickel, iron, etc.

TABLE 1.—*Miscellaneous bearing bronze specifications in present use*

## A. BRONZES WITH LOW LEAD CONTENTS

| Alloy | Composition (in per cent) |         |         |         |         |         |         |         |            |         |         |         |                   |               |                         |
|-------|---------------------------|---------|---------|---------|---------|---------|---------|---------|------------|---------|---------|---------|-------------------|---------------|-------------------------|
|       | Copper                    |         | Tin     |         | Lead    |         | Zinc    |         | Phosphorus |         | Nickel  |         | Antimony, maximum | Iron, maximum | Other elements, maximum |
|       | Minimum                   | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum    | Maximum | Minimum | Maximum |                   |               |                         |
| 1     | 87.0                      | 90.0    | 9.0     | 10.0    | —       | 0.7     | 0.2     | 0.5     | 0.6        | 0.9     | —       | —       | —                 | —             | 2.5                     |
| 2     | 87.7                      | 89.7    | 9.0     | 11.0    | 0.5     | 1.5     | —       | —       | .2         | .4      | —       | —       | —                 | —             | 2.6                     |
| 3     | 85.7                      | 87.7    | 9.0     | 11.0    | 2.5     | 3.5     | —       | —       | .2         | .4      | —       | —       | —                 | —             | 2.6                     |
| 4     | 86.0                      | 89.0    | 9.0     | 11.0    | —       | —       | .2      | 1.0     | 3.0        | —       | —       | —       | 0.06              | 4.0           | 4.0                     |
| 5     | 84.0                      | 85.5    | 14.5    | 15.5    | —       | —       | .5      | —       | —          | .09     | .12     | —       | —                 | —             | 1.4                     |
| 6     | 85.0                      | 89.0    | 7.5     | 8.5     | .75     | 1.5     | 2.25    | 4.25    | .05        | 1.0     | —       | —       | —                 | —             | 4.45                    |
| 7     | 86.0                      | 88.5    | 9.0     | 11.0    | 1.25    | 1.6     | 1.5     | 2.5     | —          | —       | —       | —       | —                 | —             | 2.25                    |
| 8     | 87.0                      | 89.0    | 9.0     | 11.0    | 2.0     | 3.0     | —       | —       | .75        | —       | —       | —       | —                 | —             | 1.25                    |
| 9     | 86.0                      | 88.0    | 9.5     | 10.5    | .6      | 1.0     | 1.5     | 2.5     | —          | —       | —       | —       | —                 | —             | 2.40                    |
| 10    | 83.5                      | 85.5    | 12.5    | 14.5    | —       | —       | 1.5     | 2.5     | —          | —       | —       | —       | —                 | —             | 2.50                    |

<sup>4</sup> H. J. French, S. J. Rosenbaum, W. LeC. Harbaugh, and H. C. Cross, Wear and Mechanical Properties of Some Railroad Bearing Bronzes at Different Temperatures, *B. S. Jour. Research*, 1 (RP13); September, 1928; also *Proc. Am. Soc. Test. Matls.*; 1928.

<sup>5</sup> H. J. French and E. M. Staples, Bearing Bronzes with and without Zinc, *B. S. Jour. Research*, 2 (RP68); June, 1929; also *Proc. Am. Soc. Test. Matls.*; 1929.

TABLE 1.—Miscellaneous bearing bronze specifications in present use—Continued

## A. BRONZES WITH LOW LEAD CONTENTS—Continued

| Alloy | Composition (in per cent) |         |         |         |         |         |         |         |            |         |         |         |                   |               |                         |
|-------|---------------------------|---------|---------|---------|---------|---------|---------|---------|------------|---------|---------|---------|-------------------|---------------|-------------------------|
|       | Copper                    |         | Tin     |         | Lead    |         | Zinc    |         | Phosphorus |         | Nickel  |         | Antimony, maximum | Iron, maximum | Other elements, maximum |
|       | Minimum                   | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum    | Maximum | Minimum | Maximum |                   |               |                         |
| 11    | 81.0                      | 83.0    | 9.0     | 11.0    | 1.5     | 3.0     | —       | 1.0     | —          | —       | 5.0     | 7.0     | —                 | —             | 4.5                     |
| 12    | 86.7                      | 87.7    | 8.45    | 9.95    | —       | —       | —       | 2.6     | 3.6        | —       | —       | —       | —                 | —             | 2.25                    |
| 13    | 83.0                      | 85.0    | 11.25   | 12.75   | —       | —       | —       | 3.0     | 4.0        | —       | —       | —       | —                 | —             | 2.75                    |
| 14    | 81.0                      | 83.0    | 9.0     | 10.5    | 2.0     | 3.0     | —       | —       | —          | —       | 5.0     | 6.5     | —                 | —             | 3.00                    |
| 15    | 86.5                      | 88.5    | 10.15   | 11.65   | —       | —       | —       | 1.1     | 2.1        | —       | —       | —       | —                 | —             | 2.25                    |
| 16    | 89.9                      | 91.9    | 8.05    | 9.55    | —       | —       | —       | —       | —          | —       | 0.30    | —       | —                 | —             | 2.05                    |
| 17    | 83.0                      | 85.0    | 9.25    | 10.75   | 2.0     | 3.0     | 3.0     | 4.0     | —          | —       | —       | —       | —                 | —             | 2.75                    |
| 18    | 86.0                      | 91.0    | 6.0     | 7.0     | 1.0     | 2.0     | 1.5     | 5.0     | —          | —       | .05     | .75     | 0.25              | 0.15          | .20                     |
| 19    | 78.0                      | 82.0    | 4.0     | 6.0     | 2.0     | 3.0     | 10.0    | 16.0    | —          | —       | .05     | .75     | .25               | .35           | .20                     |
| 20    | 86.0                      | 89.0    | 7.5     | 11.0    | —       | —       | .30     | 1.5     | 4.5        | —       | .05     | .75     | .25               | .25           | .40                     |
| 21    | 82.0                      | 85.0    | 13.0    | 15.0    | —       | .20     | —       | 1.5     | —          | .05     | —       | .75     | .50               | .10           | .30                     |
| 22    | 86.0                      | 89.0    | 9.0     | 11.0    | 1.0     | 2.50    | —       | —       | —          | .25     | —       | —       | —                 | —             | .50                     |
| 23    | 88.0                      | 90.0    | 10.0    | 12.0    | —       | —       | —       | —       | 0.10       | .30     | —       | —       | —                 | —             | .50                     |
| 24    | 87.0                      | 89.0    | 6.5     | 7.5     | 1.25    | 2.75    | 2.25    | 3.75    | —          | —       | —       | —       | .20               | .30           | .10                     |
| 25    | 87.0                      | 89.0    | 9.5     | 10.5    | 1.0     | 3.0     | —       | —       | —          | —       | —       | —       | —                 | —             | .35                     |

## B. BRONZES WITH MEDIUM LEAD CONTENTS (4 TO 12 PER CENT)

|    |      |      |      |      |      |      |     |      |      |      |   |      |      |      |      |
|----|------|------|------|------|------|------|-----|------|------|------|---|------|------|------|------|
| 1  | 81.0 | 83.5 | 6.5  | 7.5  | 6.5  | 7.5  | 2.5 | 4.0  | —    | 0.10 | — | —    | —    | —    | 3.5  |
| 2  | 78.5 | 81.5 | 9.0  | 11.0 | 9.0  | 11.0 | —   | 1.0  | —    | —    | — | —    | —    | —    | 3.5  |
| 3  | 81.0 | 87.0 | 3.0  | 6.0  | 4.0  | 7.5  | 4.0 | 6.0  | —    | —    | — | —    | —    | —    | 3.0  |
| 4  | 84.0 | 86.0 | 4.5  | 5.5  | 8.0  | 10.0 | —   | —    | —    | 1.50 | — | —    | 0.20 | 0.20 | .35  |
| 5  | 83.0 | 86.0 | 4.5  | 6.0  | 8.0  | 10.0 | —   | —    | —    | 2.00 | — | —    | —    | —    | .25  |
| 6  | 78.5 | 80.5 | 11.0 | 13.0 | 6.5  | 8.5  | —   | —    | 1.00 | —    | — | —    | —    | —    | 5.00 |
| 7  | 78.5 | 82.5 | 9.0  | 10.5 | 9.0  | 10.5 | —   | .50  | .60  | .90  | — | —    | —    | —    | 2.90 |
| 8  | 78.5 | 81.5 | 6.5  | 8.5  | 10.0 | 12.0 | 1.0 | 2.5  | —    | —    | — | —    | —    | —    | 5.00 |
| 9  | 77.0 | 82.0 | 9.0  | 11.0 | 8.0  | 11.0 | —   | —    | .7   | 1.0  | — | —    | —    | —    | 1.00 |
| 10 | 84.0 | 86.0 | 4.0  | 6.0  | 4.0  | 6.0  | 4.0 | 6.0  | —    | .05  | — | 0.75 | .25  | .25  | .20  |
| 11 | 80.0 | 83.0 | 2.0  | 3.0  | 5.0  | 7.0  | 8.0 | 12.0 | —    | —    | — | —    | —    | —    | 1.00 |
| 12 | 82.0 | 85.0 | 7.0  | 9.0  | 7.0  | 9.0  | —   | .25  | .30  | .60  | — | 1.00 | .15  | .15  | .40  |
| 13 | 83.0 | 86.0 | 4.5  | 5.5  | 4.5  | 5.5  | 4.5 | 5.5  | —    | —    | — | —    | .25  | .35  | 3.50 |
| 14 | 78.5 | 81.5 | 9.0  | 11.0 | 9.0  | 11.0 | —   | .75  | .05  | .25  | — | —    | —    | —    | .25  |

## C. BRONZES WITH HIGH LEAD CONTENTS (12 TO 30 PER CENT)

|    |      |      |      |       |       |       |      |      |      |      |     |      |      |      |      |
|----|------|------|------|-------|-------|-------|------|------|------|------|-----|------|------|------|------|
| 1  | 73.0 | 79.0 | 6.5  | 8.0   | 15.5  | 18.5  | —    | —    | 1.00 | —    | —   | —    | —    | —    | 5.00 |
| 2  | 75.0 | 79.0 | 7.0  | 9.0   | 13.0  | 17.0  | —    | —    | 1.00 | —    | —   | —    | —    | —    | 5.00 |
| 3  | 68.0 | 72.0 | 7.0  | 9.0   | 16.0  | 19.0  | —    | —    | 1.00 | —    | —   | 2.50 | 4.50 | —    | 6.50 |
| 4  | 73.0 | 77.0 | 10.5 | 11.5  | 12.0  | 14.0  | 0.50 | 1.50 | —    | —    | —   | —    | —    | —    | .50  |
| 5  | 72.0 | 76.0 | 4.0  | 5.0   | 18.0  | 22.0  | .50  | 1.0  | —    | —    | —   | —    | —    | —    | 6.50 |
| 6  | 66.0 | 77.0 | 6.0  | 8.0   | 23.0  | 27.0  | —    | —    | 1.0  | —    | —   | —    | —    | —    | 4.00 |
| 7  | 71.0 | 74.5 | 3.25 | 4.25  | 22.0  | 25.0  | —    | —    | —    | —    | —   | —    | —    | —    | 3.75 |
| 8  | 69.0 | 71.0 | 1.0  | 2.0   | 28.0  | 30.0  | —    | —    | —    | —    | —   | —    | —    | —    | 2.00 |
| 9  | 73.0 | 80.0 | 5.0  | 7.0   | 15.0  | 20.0  | —    | .50  | —    | 0.05 | —   | 1.00 | 0.25 | 0.25 | .60  |
| 10 | 75.5 | 78.5 | 7.25 | 8.75  | 13.50 | 16.50 | —    | .50  | —    | .25  | —   | .50  | .25  | .25  | .75  |
| 11 | 73.0 | —    | 9.50 | 10.50 | 12.50 | 15.50 | .50  | 2.50 | —    | —    | —   | .25  | .20  | .20  | .20  |
| 12 | 69.0 | 71.0 | 4.50 | 5.50  | 23.50 | 26.50 | —    | —    | —    | —    | —   | .25  | .20  | .20  | .10  |
| 13 | 69.0 | 71.0 | 8.50 | 9.50  | 18.50 | 22.50 | —    | —    | —    | —    | —   | .25  | .20  | .20  | .10  |
| 14 | 63.0 | 72.0 | 3.0  | 6.0   | 23.0  | 28.0  | —    | —    | —    | 2.0  | 3.0 | —    | —    | —    | 2.00 |

The subject of impurities is of considerable economic importance in the production of bearing bronzes, the cost of bearings to the consumer being governed largely by the kind and amount of impurities. It is advantageous, therefore, to both the consumer and manufacturer to know the effects of different impurities on the properties. This investigation on the effect of various additions on

the properties of bronzes forms one phase of the general study of bearing bronzes which has been in progress for over two years in cooperation with the Bunting Brass & Bronze Co. on the research associate plan.<sup>6</sup>

## II. ALLOYS STUDIED

The program consisted of a study of the effects of various additions, namely, zinc, phosphorus, nickel, and antimony on the properties of copper-tin-lead alloys, most of the alloys studied being selected from the group in common manufacture. In order to widen the scope of the investigation, some alloys, not usually considered as bearing metals, were included.

Five groups of alloys were prepared. In the first group the additions were kept as low as was practicable. In the four additional groups approximately the same ratios of copper-tin-lead were maintained as in the first group, but each group contained an additional metal. These additions consisted of zinc (4 per cent), phosphorus (0.05 per cent), nickel (2 per cent), and antimony (1 per cent). The composition of the various test bronzes are given in Table 2.

TABLE 2.—*Chemical compositions of bronzes studied*

| Alloy No.        | Used for wear tests (W) or mechanical tests (M) | Chemical composition (in per cent)           |                                          |                                        |                              |                            |                            |                            |
|------------------|-------------------------------------------------|----------------------------------------------|------------------------------------------|----------------------------------------|------------------------------|----------------------------|----------------------------|----------------------------|
|                  |                                                 | Copper                                       | Tin                                      | Lead                                   | Zinc                         | Phosphorus                 | Nickel                     | Antimony                   |
| 10, base alloy   | { W<br>M                                        | 96.5<br>95.4                                 | 1.8<br>2.1                               | 1.8<br>2.0                             | —<br>—                       | —<br>—                     | —<br>—                     | —<br>—                     |
| 10Z <sup>1</sup> | { W<br>M                                        | 91.4<br>92.5                                 | 2.0<br>2.0                               | 1.9<br>1.8                             | 4.5<br>3.7                   | —<br>—                     | —<br>—                     | —<br>—                     |
| 10P <sup>2</sup> | WM                                              | 96.3                                         | 1.6                                      | 1.9                                    | —                            | 0.05                       | —                          | —                          |
| 10N <sup>3</sup> | WM                                              | 95.5                                         | .9                                       | 1.6                                    | —                            | —                          | 2.0                        | —                          |
| 10A <sup>4</sup> | WM                                              | 95.1                                         | 1.8                                      | 1.8                                    | —                            | —                          | —                          | 1.0                        |
| 20, base alloy   | { W<br>M                                        | 73.7<br>73.1                                 | 11.8<br>12.8                             | 14.4<br>14.1                           | —<br>—                       | —<br>—                     | —<br>—                     | —<br>—                     |
| 20Z              | { W<br>M                                        | 69.4<br>70.5                                 | 12.1<br>11.9                             | 15.1<br>13.8                           | 3.2<br>3.8                   | —<br>—                     | —<br>—                     | —<br>—                     |
| 20P              | WM                                              | 72.9                                         | 12.5                                     | 14.2                                   | —                            | .058                       | —                          | —                          |
| 20N              | WM                                              | 73.1                                         | 12.5                                     | 12.3                                   | —                            | —                          | 2.1                        | —                          |
| 20A              | WM                                              | 72.7                                         | 12.0                                     | 13.4                                   | —                            | —                          | —                          | 1.2                        |
| 27, base alloy   | { W<br>M<br>W<br>W                              | 80.4<br>79.8<br>80.5<br>76.5                 | 10.0<br>10.3<br>9.8<br>9.4               | 9.5<br>9.6<br>9.6<br>9.8               | —<br>—<br>—<br>—             | —<br>—<br>—<br>4.1         | —<br>—<br>—<br>—           | —<br>—<br>—<br>—           |
| 27Z              | { W<br>M<br>W                                   | 76.4<br>76.4<br>77.4                         | 10.1<br>9.1<br>10.1                      | 9.1<br>4.4<br>10.1                     | 4.4<br>—<br>3.3              | —<br>—<br>—                | —<br>—<br>—                | —<br>—<br>—                |
| 27P              | WM                                              | 80.7                                         | 9.7                                      | 9.9                                    | —                            | .045                       | —                          | —                          |
| 27N              | WM                                              | 79.2                                         | 9.7                                      | 9.1                                    | —                            | —                          | 1.9                        | —                          |
| 27A              | WM                                              | 80.5                                         | 9.6                                      | 8.6                                    | —                            | —                          | —                          | 1.1                        |
| 72, base alloy   | { W<br>M                                        | 85.8<br>85.3                                 | 7.3<br>7.3                               | 6.8<br>7.2                             | —<br>—                       | —<br>—                     | —<br>—                     | —<br>—                     |
| 72Z              | { W<br>M                                        | 82.2<br>82.5                                 | 6.8<br>7.2                               | 7.0<br>6.7                             | 4.0<br>3.6                   | —<br>—                     | —<br>—                     | —<br>—                     |
| 72P              | WM                                              | 85.7                                         | 7.5                                      | 6.9                                    | —                            | .054                       | —                          | —                          |
| 72N              | WM                                              | 84.1                                         | 7.1                                      | 6.7                                    | —                            | —                          | 2.0                        | —                          |
| 72A              | WM                                              | 84.6                                         | 7.2                                      | 7.0                                    | —                            | —                          | —                          | 1.2                        |
| 96, base alloy   | { W<br>W<br>M<br>W<br>W<br>M                    | 88.1<br>88.5<br>88.4<br>88.9<br>84.8<br>84.8 | 10.0<br>9.5<br>10.3<br>9.3<br>9.9<br>9.5 | 2.0<br>2.0<br>1.5<br>2.1<br>2.1<br>2.0 | —<br>—<br>—<br>—<br>—<br>3.7 | —<br>—<br>—<br>—<br>—<br>— | —<br>—<br>—<br>—<br>—<br>— | —<br>—<br>—<br>—<br>—<br>— |

<sup>1</sup>Z, with zinc addition.

<sup>2</sup>P, with phosphorus addition.

<sup>3</sup>N, with nickel addition.

<sup>4</sup>A, with antimony addition.

TABLE 2.—*Chemical compositions of bronzes studied—Continued*

| Alloy No.       | Used for wear tests (W) or mechanical tests (M) | Chemical composition (in per cent) |                |                |              |            |        |          |
|-----------------|-------------------------------------------------|------------------------------------|----------------|----------------|--------------|------------|--------|----------|
|                 |                                                 | Copper                             | Tin            | Lead           | Zinc         | Phosphorus | Nickel | Antimony |
| 96P             | WM                                              | 88.4                               | 9.6            | 2.1            | —            | 0.043      | —      | —        |
| 96N             | WM                                              | 87.0                               | 9.0            | 2.0            | —            | —          | 1.8    | —        |
| 96A             | WM                                              | 87.0                               | 9.6            | 2.3            | —            | —          | —      | 1.1      |
| 125, base alloy | { W<br>M                                        | { 75.3<br>76.6                     | { 4.5<br>4.6   | { 20.1<br>18.9 | —            | —          | —      | —        |
| 125Z            | { W<br>M                                        | { 72.8<br>73.0                     | { 4.3<br>4.3   | { 19.1<br>18.5 | { 3.7<br>4.2 | —          | —      | —        |
| 125P            | WM                                              | 75.0                               | 4.8            | 19.8           | —            | .048       | —      | —        |
| 125N            | WM                                              | 74.9                               | 4.4            | 18.7           | —            | —          | 1.9    | —        |
| 125A            | WM                                              | 78.3                               | 4.3            | 15.6           | —            | —          | —      | 1.2      |
| 133, base alloy | { W<br>M                                        | { 68.2<br>75.2                     | { 2.4<br>1.5   | { 28.7<br>23.2 | —            | —          | —      | —        |
| 133Z            | { W<br>M                                        | { 66.3<br>71.0                     | { 2.2<br>1.4   | { 27.8<br>23.8 | { 3.7<br>3.8 | —          | —      | —        |
| 133P            | WM                                              | 72.5                               | 1.8            | 25.7           | —            | .055       | —      | —        |
| 133N            | WM                                              | 73.3                               | 1.5            | 23.1           | —            | —          | 2.0    | —        |
| 133A            | WM                                              | 71.1                               | 1.5            | 25.9           | —            | —          | —      | 1.1      |
| 143, base alloy | { W<br>M                                        | { 85.2<br>84.8                     | { 14.7<br>15.0 | —              | —            | —          | —      | —        |
| 143Z            | { W<br>M                                        | { 81.1<br>82.0                     | { 14.5<br>13.8 | —              | { 4.4<br>4.2 | —          | —      | —        |
| 143P            | WM                                              | 85.0                               | 14.9           | —              | —            | .051       | —      | —        |
| 143N            | WM                                              | 83.4                               | 14.4           | .1             | —            | —          | 1.9    | —        |
| 143A            | WM                                              | 83.4                               | 15.1           | .1             | —            | —          | —      | 1.1      |

### III. PREPARATION OF THE TEST CASTINGS

In order that the structure and properties of the test castings would approximate those of the average bushings used in the automotive and allied industries, the test castings were of relatively thin section. The dimensions of these test castings, together with the methods of gating, are illustrated in Figure 1.

In the preparation of these castings 1,500 pounds of a base alloy of copper and tin of approximately 90 per cent copper and 10 per cent tin were first melted in an open-flame gas-fired furnace and poured into small notched bar ingots. These ingots were used as the base alloy for subsequent melts; the necessary pure metals being added in order to prepare alloys of desired compositions. These smaller melts, weighing about 40 pounds each, were made in a gas-fired crucible furnace. Additions of zinc, lead, tin, antimony, or phosphorus were added to the molten base alloy after the crucible had been removed from the furnace and carefully skimmed. Additions of copper and nickel were made at the time of charging the crucible. In all cases the metal was melted under a slag of approximately 50 per cent borax and 50 per cent limestone.

All of the heats were poured at temperatures as close as practicable to 2,000° F. (1,095° C.). Deviations from this pouring temperature were slight, with the exception of the alloys Nos. 10 and 133. (Table 2.) The high copper content of alloy No. 10 necessitated a higher pouring temperature, about 2,100° F. (1,150° C.), and on account of the high lead content of alloy No. 133 it was found desirable to pour this alloy at a slightly lower temperature, about 1,950° F. (1,065° C.). Observations made during the process of casting

showed that each of these elements has a strong effect in preventing segregation of lead. It was also noted that melts containing antimony and nickel showed a considerable tendency to oxidize in the crucible and also in the mold.

The casting conditions were kept as nearly constant as possible because it was shown by Carpenter and Elam,<sup>7</sup> Karr,<sup>8</sup> and Rowe<sup>9</sup> that variations in these conditions might appreciably affect the properties of bronzes.

#### IV. TEST METHODS

In outlining the program special attention was given to the causes of bearing failure in service. Bearings which have failed in service are frequently termed "worn out." This term may often be a misnomer, as wear often plays only a minor part in rendering the bearings unserviceable. Repeated pounding stresses frequently cause a large percentage of failures. A survey of the possible causes of bearing failure indicated that the following properties deserved study: Wear resistance, resistance to repeated pounding, resistance to impact (single-blow), and hardness.

In the work previously reported,<sup>10</sup> wear resistance tests were made both with and without a lubricant, but comparisons of the alloys were made wholly on the basis of the dry or unlubricated tests. "Lubricated tests" would be of value in bearing metal testing technique if such tests were not so difficult to control or did not require such extensive periods of time.

Under conditions of complete film lubrication the wear rate is extremely low. Conditions giving boundary lubrication have many experimental difficulties, so it was decided to run this series of experiments in the unlubricated condition on the Amsler machine.<sup>11</sup>

All wear resistance tests were run in duplicate. Each bronze specimen was tested against a standard steel specimen, a new specimen being used in each case. The steel used throughout this investigation was an oil-hardened carbon steel containing 0.93 per cent carbon. This steel was selected because its surface hardness after treatment is comparable to that of case-hardened low-carbon steel generally used for shafts in bronze bearings. The heat treatment and properties have been previously described.<sup>12</sup>

In the wear-resistance tests the total pressure between the specimens was about 37.5 pounds. The unit contact pressure, as calculated by the Hertz<sup>13</sup> formula, for line contact varied from 24,200 lbs./in.<sup>2</sup> to 30,600 lbs./in.<sup>2</sup>, the variation being due to the lateral oscillation of the upper specimen, which is a characteristic feature of the Amsler machine. As these pressures are known to be above the proportional limits of the various bronzes tested, it is believed that the wear rates of the alloys were accelerated accordingly.

<sup>7</sup> H. C. H. Carpenter and Miss C. F. Elam, Causes of Unsound Castings of Admiralty Bronze, *J. Inst. Met.*, **19**, p. 155, 1918.

<sup>8</sup> C. P. Karr, Standard Test Specimens of Zinc Bronze, *B. S. Tech. Paper No. 59*; 1916.

<sup>9</sup> F. W. Rowe, The Effect of Casting Temperature on the Physical Properties of a Sand-Cast Zinc-Bronze, *J. Inst. Metals*, **31**, p. 217; 1924.

<sup>10</sup> See footnote 5, p. 350.

<sup>11</sup> See footnotes 4 and 5, p. 350.

<sup>12</sup> See footnote 5, p. 350.

<sup>13</sup> Hertz, *Miscellaneous Papers*, MacMillan & Co. (Ltd.), p. 163; 1896. A more convenient reference is F. H. Buhiman, Factors Governing the Design of Roller Bearings for Roll Necks, *Iron & Steel Engr.*, **4**, p. 302; June 1927.

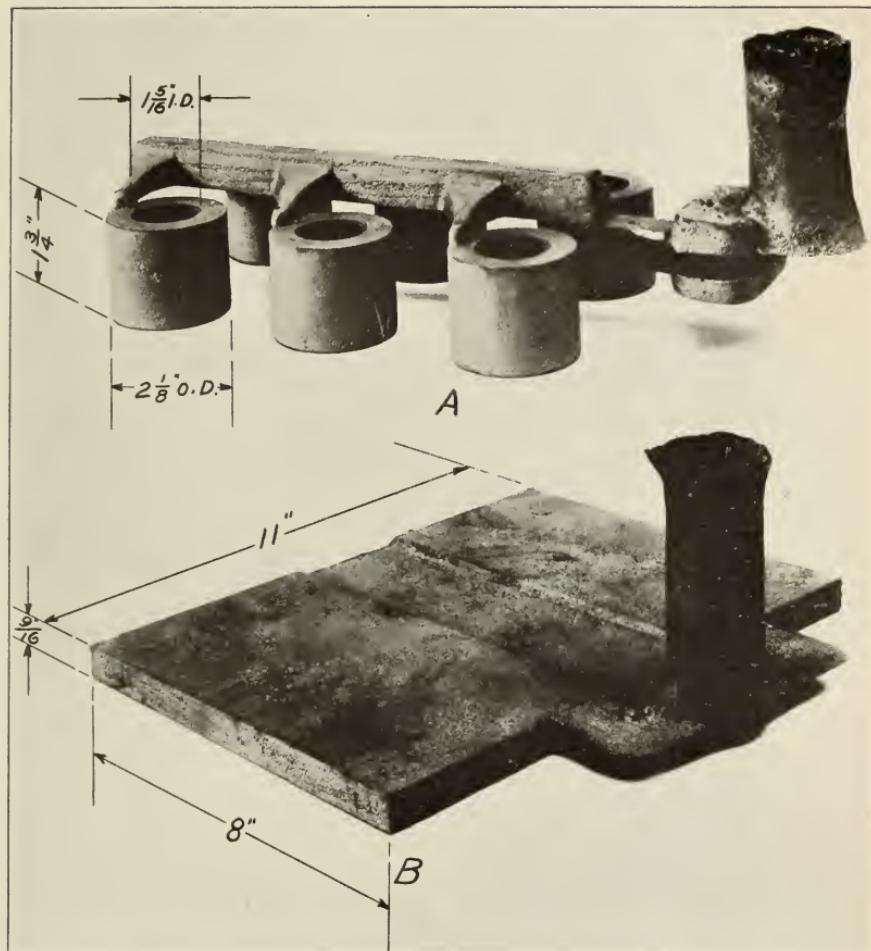


FIGURE 1.—*Test castings*

*A*, For wear test specimens; *B*, for impact, pounding and hardness tests.

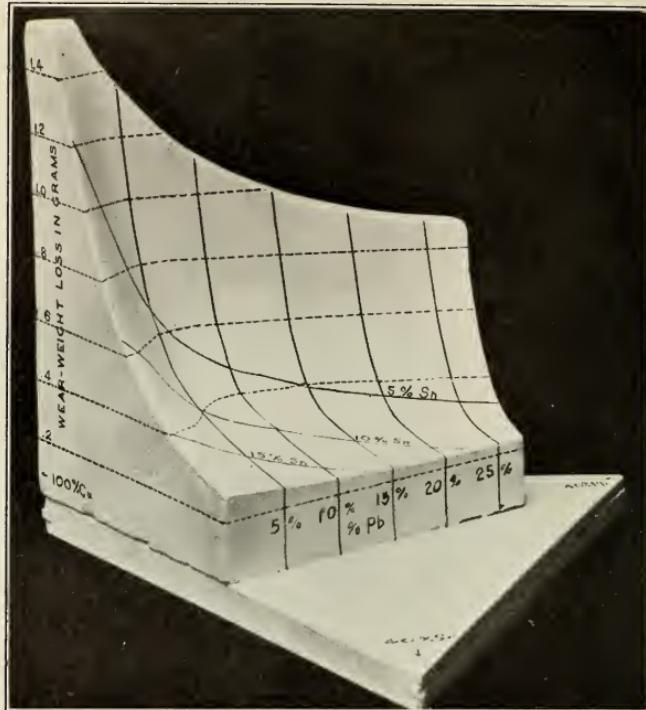


FIGURE 3.—Model showing relation for bronzes investigated in Cu-Sn-Pb system

Wear expressed in weight loss per 10,000 revolutions. Test conditions are described in detail in the reference given in footnote 1 of the text. Tests made at atmospheric temperatures.

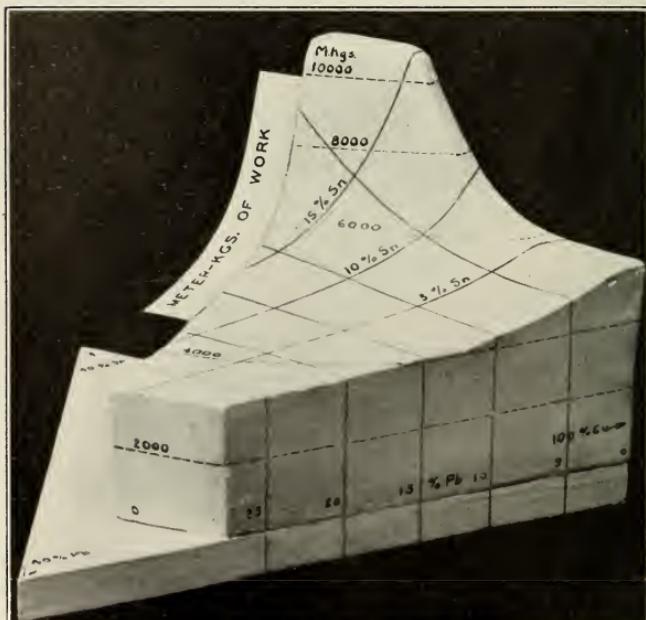


FIGURE 4.—Model showing relation of work done in meter-kilograms per 10,000 revolutions for bronzes investigated in the Cu-Sn-Pb system

The meter-kilogram of work is determined from the torque indicator of the Amsler wear machine, and is directly proportional to the frictional force between the steel and the bronze specimens. Tests made at atmospheric temperatures.

The equipment and methods of test used for the determination of resistance to pounding, resistance to impact, and Brinell hardness have been previously described.<sup>14</sup>

The forms of test specimens used for the determination of wear, resistance to impact, and resistance to repeated pounding are shown in Figure 2.

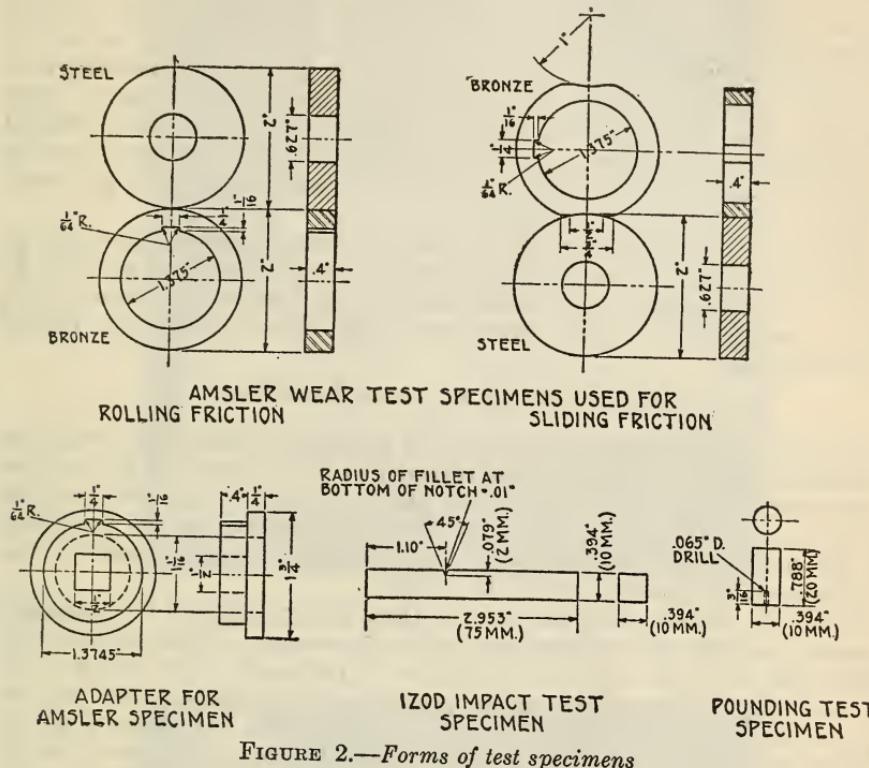


FIGURE 2.—Forms of test specimens

## V. RESULTS AND DISCUSSION

### 1. COPPER-TIN-LEAD BRONZES WITHOUT ADDITIONS

#### (a) WEAR RESISTANCE

The results of tests on wear resistance of the alloys without additions are shown by the ternary model (fig. 3), in which the ordinates show weight losses for 10,000 revolutions obtained with the different alloys represented in the base of the model. It will be noted that an increase in the content of tin and lead, either collectively or separately, reduced the rate of wear. Other information of value was obtained from these tests, particularly the frictional force between the bronze and the steel as measured by the torque indicator. Some of the specimens tested for wear resistance showed a tendency to "flat-wheel" or become "out of round" during testing. Alloys having high resistance to pounding do not "flat-wheel" during the test, while alloys having low resistance to pounding show the greatest tendency toward the "flat-wheel" effect.

<sup>14</sup> See footnote 5, p. 350.

The average results indicative of the relative friction between the bronzes and the steel specimens during testing are given in the ternary model, as meter-kilograms of work recorded by the torque indicator. (Fig. 4.) Attention is called to the fact that the coefficient of friction of a bearing material with a journal, tested under unlubricated conditions, has no apparent relationship to the coefficient of friction of the same bearing and shaft if adequate lubrication is maintained. When lubrication is incomplete, such as during starting or failure of the lubricant, the coefficient of friction of the journal and bearing is of importance. In order to minimize damage and seizure due to overheating, a low coefficient of friction is desirable. Attention is called to the increase in the number of kilograms of work recorded by the torque indicator with bronzes having a lead content below 5 per cent. (Fig. 4.)

Tests on wear resistance were made at room temperature and at 350° F. (175° C.). The order of comparison of the alloys at 350° F. (175° C.) agreed quite well with that obtained at room temperature, but a consistently higher wear rate was observed at the higher temperature.

#### (b) RESISTANCE TO REPEATED POUNDING

The model showing the resistance to pounding of the alloys without additions (fig. 5) is based on the number of blows required to produce 5 per cent deformation (upset) of the specimens. As some of the specimens did not deform 5 per cent, the resistance to pounding of the series with the additions was measured on the basis of the percentage deformation after 100 blows.

It will be noted from the model that the resistance to pounding increased as the ratio of copper to tin decreased. This was investigated only with tin contents as high as 15 per cent. The effect of tin on increasing the resistance to pounding is probably due to two causes; first, a strengthening of the alpha solid solution of tin in copper, and second, a further stiffening of the resulting structure by the precipitation of the delta microconstituent according to the reaction  $\text{beta} \rightarrow \text{alpha} + \text{delta}$ .

It would seem that additions of lead would lower considerably the pounding resistance, but it should be remembered that the ratio of copper to tin is of prime importance, because it is largely the matrix of the alloy that resists deformation and not the free lead contained.

#### (c) RESISTANCE TO IMPACT

Impact tests by the Izod method were made on all of the alloys studied. The value of this test for comparing bearing metals is largely dependent on the design of the bearing. Bearings completely supported need not necessarily be of high toughness. On the other hand, if the bearing has overhanging flanges or unsupported parts which might be subjected to shock, the relative toughness of the bearing metal is of importance.

The notch toughness values obtained on the alloys without additions are shown in a ternary model. (Fig. 6.) It was found that an increase in tin, to about 8 per cent, had little effect. When the tin content was above that amount, a sharp decrease in toughness resulted, due primarily to the brittleness of the alpha-delta micro-

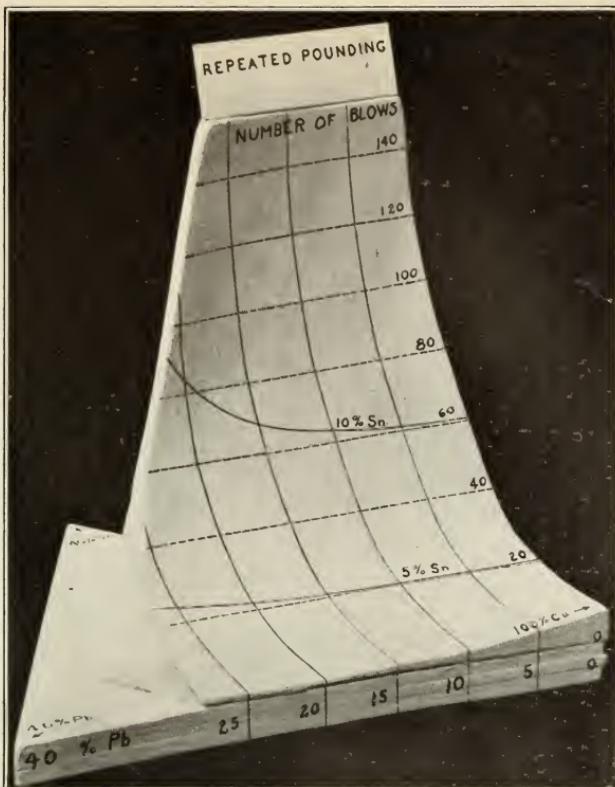


FIGURE 5.—Model showing relation of repeated pounding for bronzes investigated in the Cu-Sn-Pb system

Test is one of "upsetting" where comparisons are based on the number of blows producing 5 per cent deformation. Tests made at atmospheric temperatures.

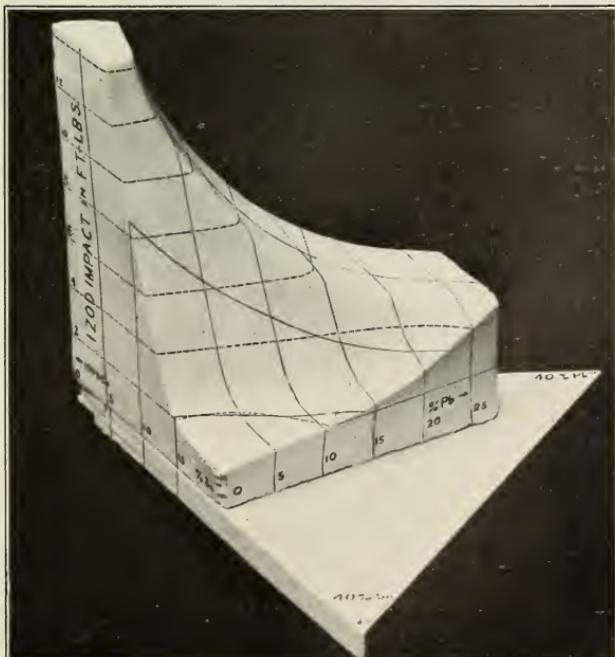


FIGURE 6.—Model showing relation of izod impact resistance for bronzes investigated in the Cu-Sn-Pb system

Tests made at atmospheric temperatures

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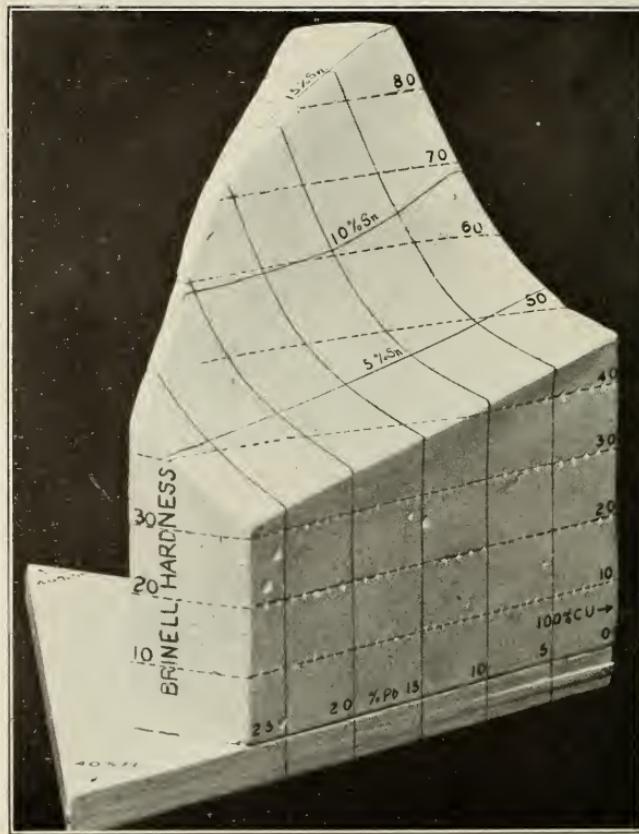


FIGURE 7.—Model showing relation of Brinell hardness for bronzes investigated in Cu-Sn-Pb system

Tests with 500 kg. load and 10 mm. ball at atmospheric temperatures.

constituent.<sup>15</sup> A progressive increase in the lead content produced a gradual decrease in toughness. Evidently this was because free lead is relatively very low in its impact toughness and also because the occurrence of the particles of lead in the bronze matrix reduced the effective cross section of the specimen.

#### (d) BRINELL HARDNESS

The results of Brinell hardness tests (10 mm ball and 500 kg load) on the alloys without additions are shown in Figure 7. The Brinell hardness reported on the alloys without additions showed the expected trends—that is, an increase in hardness with an increase in the tin content and a gradual decrease with a progressive increase in the lead content. Attention is called to the fact that no definite relationship has, as yet, been found between hardness and resistance to pounding. Alloys of the same hardness may differ in resistance to pounding, while, on the other hand, alloys of different hardnesses may have the same resistance to pounding.

### 2. COPPER-TIN-LEAD BRONZES WITH VARIOUS ADDITIONS

A comparison of the various properties determined on the copper-tin-lead bronzes with and without additions of 4 per cent zinc, 0.05 per cent phosphorus, 2 per cent nickel, and 1 per cent antimony is given in Figures 8, 9, 10, and 11.

#### (a) EFFECT OF 4 PER CENT ZINC

Zinc is frequently added to copper-tin alloys as a deoxidizer to improve their soundness. The constitution and mechanical properties of these alloys, known as copper-rich kalchoids, have been determined by a number of investigators, Hoyt,<sup>16</sup> Guillet,<sup>17</sup> Guillet and Revillon,<sup>18</sup> Thurston,<sup>19</sup> Miller.<sup>20</sup> Portevin and Nusbaumer<sup>21</sup> reported results from a Derihon machine and found that bronze alloys containing about 2.5 per cent zinc with 5 to 10 per cent tin had higher wear resistance than alloys without zinc, but having high tin contents (13 to 19 per cent).

(1) *Structure.*—The micrographs given in this report show the effects on the structure of the additions investigated, namely, 4 per cent zinc, 0.05 per cent phosphorus, 2 per cent nickel, and 1 per cent antimony, on a copper-tin-lead alloy which was basically 80 per cent copper, 10 per cent tin, and 10 per cent lead. Figures 12, 13, 14, 15, and 16 show the structures of these alloys with and without the additions in the unetched and etched conditions.

The addition of 4 per cent zinc to the base alloy produced no change in either the distribution or the segregation of lead. (Figs. 13 (a) and (b).) A comparison of Figures 12 (b) and 13 (b) shows that the addition of 4 per cent zinc increased the relative amount

<sup>15</sup> W. L. Kent, The Brittle Ranges of Bronze, *J. Inst. of Metals (British)*, 35, pp. 45-51; 1926.

<sup>16</sup> S. L. Hoyt, On the Copper-Rich Kalchoids, *J. Inst. Metals*, 10, p. 235; 1913.

<sup>17</sup> L. Guillet, Etude Générale des Tritons Spéciaux, *Rev. de Met., Memoirs*, 3, p. 243; 1906.

<sup>18</sup> Guillet and Revillon, Determinations of the Coefficient of Equivalence for Special Bronzes, *Rev. Met. Mem.*, 7, p. 429; 1910.

<sup>19</sup> R. H. Thurston, Materials of Engineering, Pt. III. Brasses, Bronzes, John Wiley & Sons (4th ed.), p. 172; 1900.

<sup>20</sup> Von Honnes v. Miller, Studien über die Einwirkung der Wichtigeren metallischer und nicht-metallischen Zusätze auf normale Kupfer-Zinn Bronze, *Metallurgie*, 9, p. 63; 1912.

<sup>21</sup> Portevin and Nusbaumer, Essais sur l'Usure des Bronzes, *Rev. de Metallurgie*, 9, p. 61; 1912.

of the eutectoid constituent (alpha and delta) over that of the alloy without additions. The increased amount of the eutectoid constituent in the zinc alloys probably accounts for the fact that the "wearing-in" period of the specimens in the Amsler test was greater than in the case of the base alloy of only copper, tin, and lead.

(2) *Wear resistance.*—In a previous paper<sup>22</sup> the effects produced on a number of bearing bronzes by the addition of 4 per cent zinc

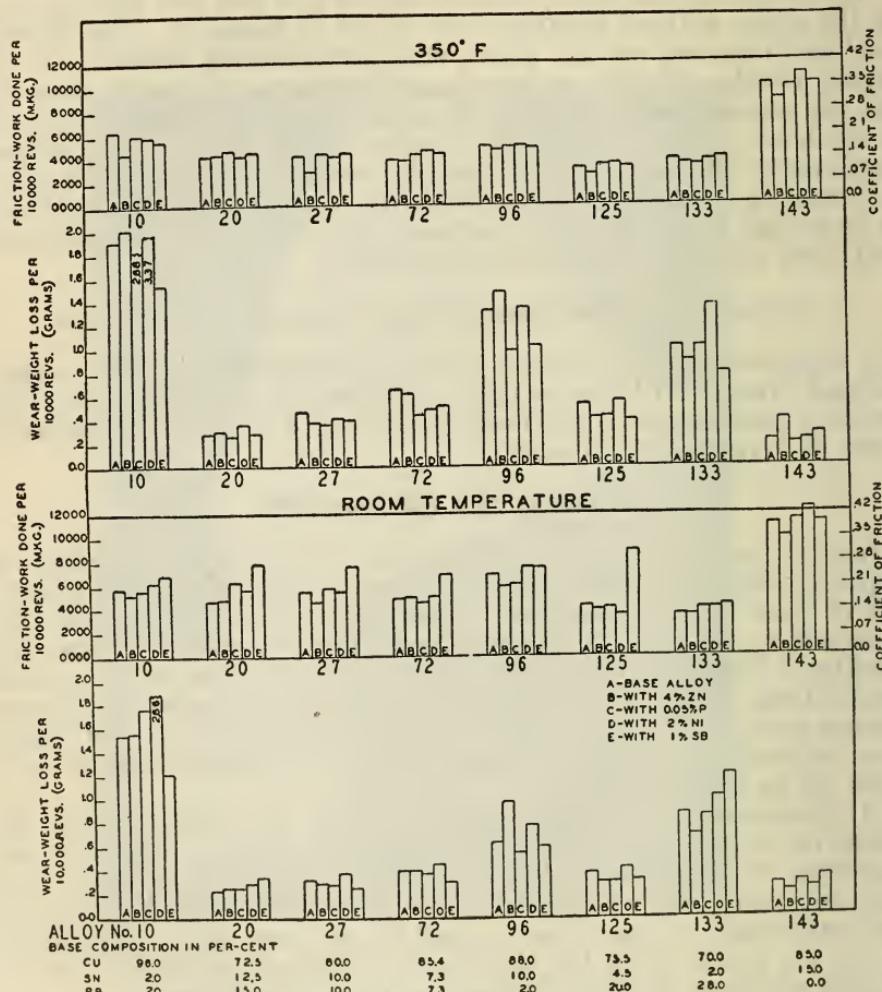


FIGURE 8.—Comparison of wear characteristics of Cu-Sn-Pb bronzes with and without other additions

Tests made at room temperatures and at 350° F. (175° C.).

have been discussed in detail. In the present investigation the rate of wear of alloy containing 4 per cent zinc at room temperature was about the same as that of the alloys containing no added impurities, with the exception of alloy No. 96. In this alloy, basically 88 per cent copper, 10 per cent tin, and 2 per cent lead, the addition of 4 per cent zinc caused an increase of about 53 per cent in the wear

<sup>22</sup> See footnote 5, p. 350.

rate at room temperature but only 12 per cent at 350° F. (175° C.). With the exception of alloy No. 96, and perhaps No. 133, it may be said that the addition of 4 per cent zinc does not have an appreciable effect on the wear resistance or the frictional forces between the copper-tin-lead alloys and steels.

(3) *Resistance to repeated pounding.*—The addition of 4 per cent zinc increased the resistance to pounding of the alloys at room temperature, but had little effect at temperatures of 350° F. (175° C.). At 600° F. (315° C.), however, the tendency was toward decreased resistance to pounding. Some of the alloys containing zinc showed less deformation at the end of 100 blows than the companion alloys

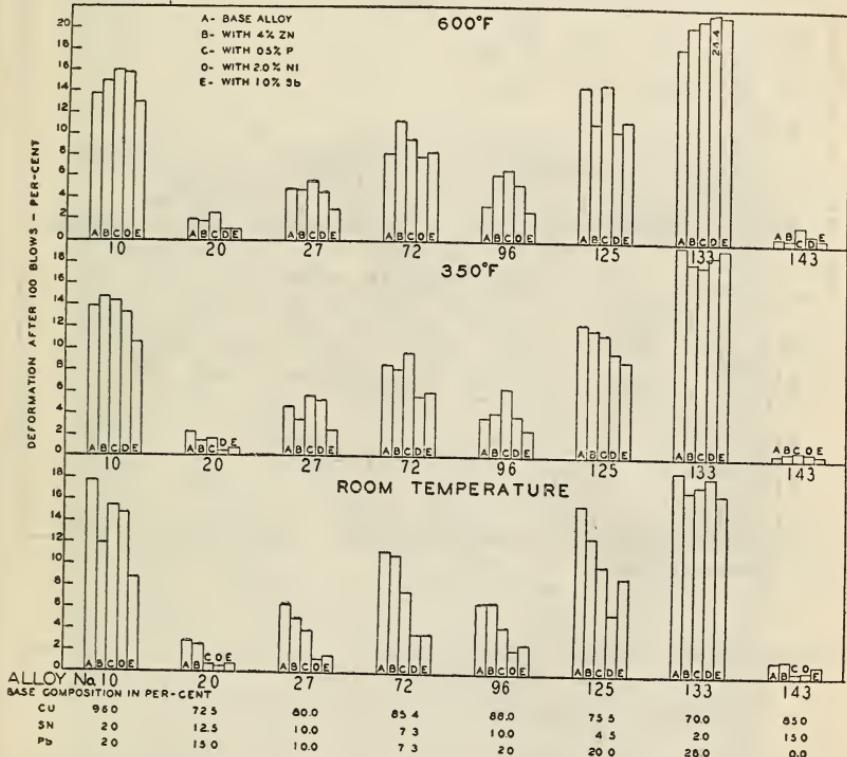


FIGURE 9.—Comparison of the resistance to repeated pounding of Cu-Sn-Pb bronzes with and without other additions

Tests made at room temperature, 350° F. (175° C.) and 600° F. (315° C.).

containing no zinc. In other cases greater deformation was obtained with the alloys containing zinc. The differences, however, were slight, and for practical purposes it may be stated that the addition of 4 per cent zinc has little effect on the resistance to deformation.

(4) *Resistance to impact.*—The addition of 4 per cent of zinc had a tendency to increase the resistance to impact of the alloys studied at both room temperature and elevated temperatures.

(5) *Brinell hardness.*—Of the alloys studied, those with zinc were consistently harder than those without zinc. The increase in hardness attributable to the addition of 4 per cent zinc was slight, however.

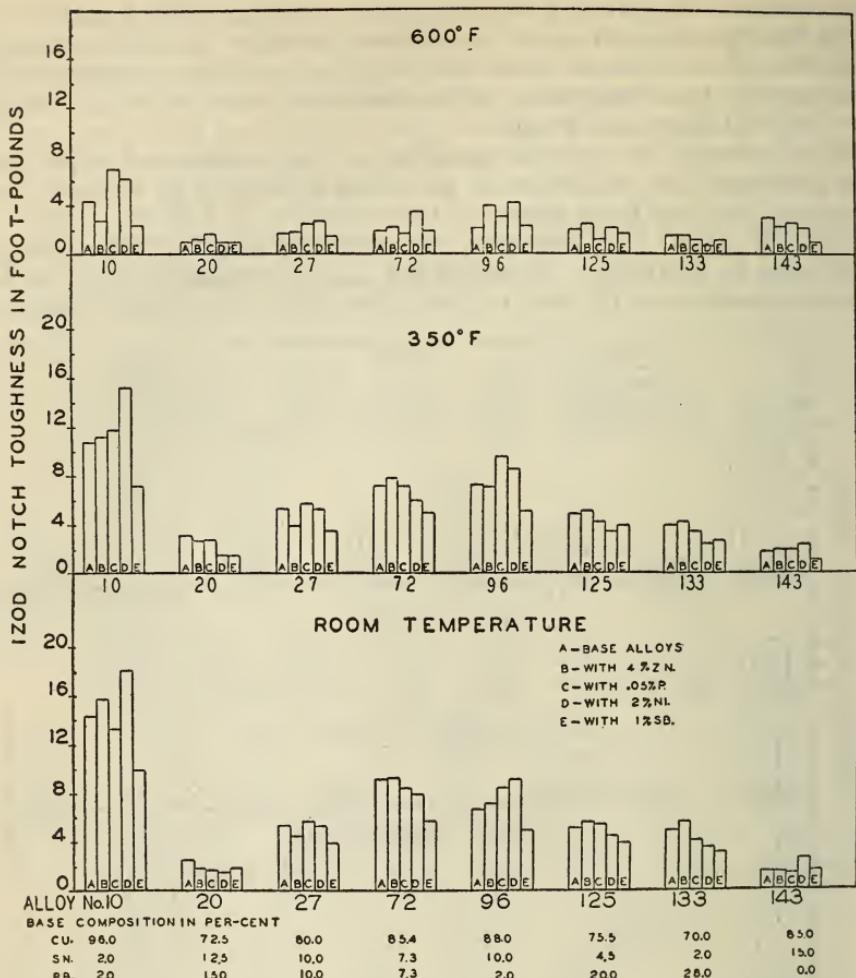


FIGURE 10.—Comparison of impact values of Cu-Sn-Pb bronzes with and without other additions

Tests made at room temperatures, 350° F. (175° C.) and 600° F. (315° C.).

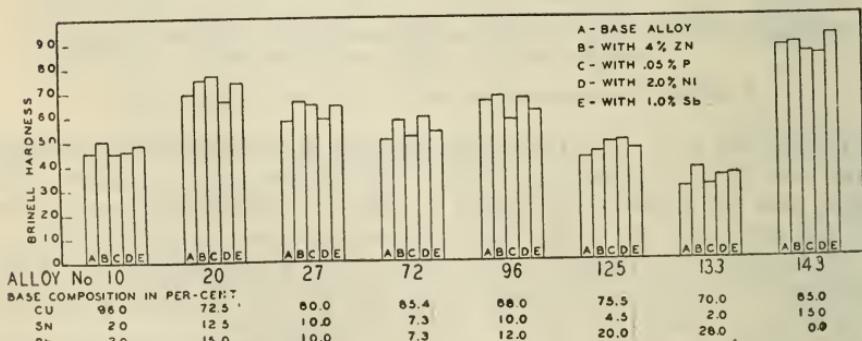


FIGURE 11.—Comparison of Brinell hardness values of Cu-Sn-Pb bronzes with and without other additions

All tests made at room temperatures.

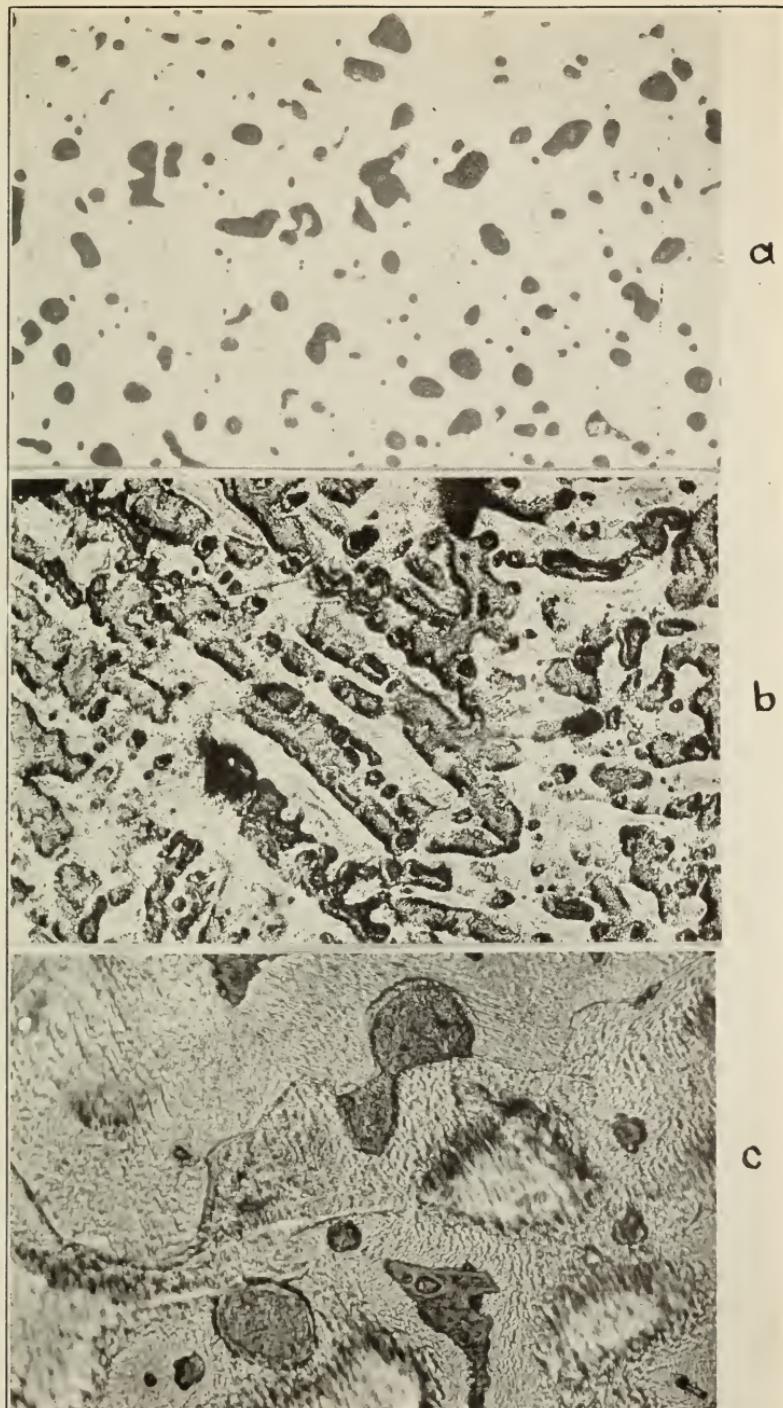


FIGURE 12.—*Microstructure of 80-10-10 bronze without additions*

*a*, Unetched,  $\times 100$ ; *b*, etched,  $\times 100$ ; *c*, etched,  $\times 500$ . Etchant 3 parts  $\text{NH}_4\text{OH}$  plus 1 part  $\text{H}_2\text{O}_2$ , followed by solution of  $\text{FeCl}_3$  in  $\text{HCl}$  (10 g  $\text{FeCl}_3$  plus 30 ml  $\text{HCl}$  plus 120 ml  $\text{H}_2\text{O}$ ).

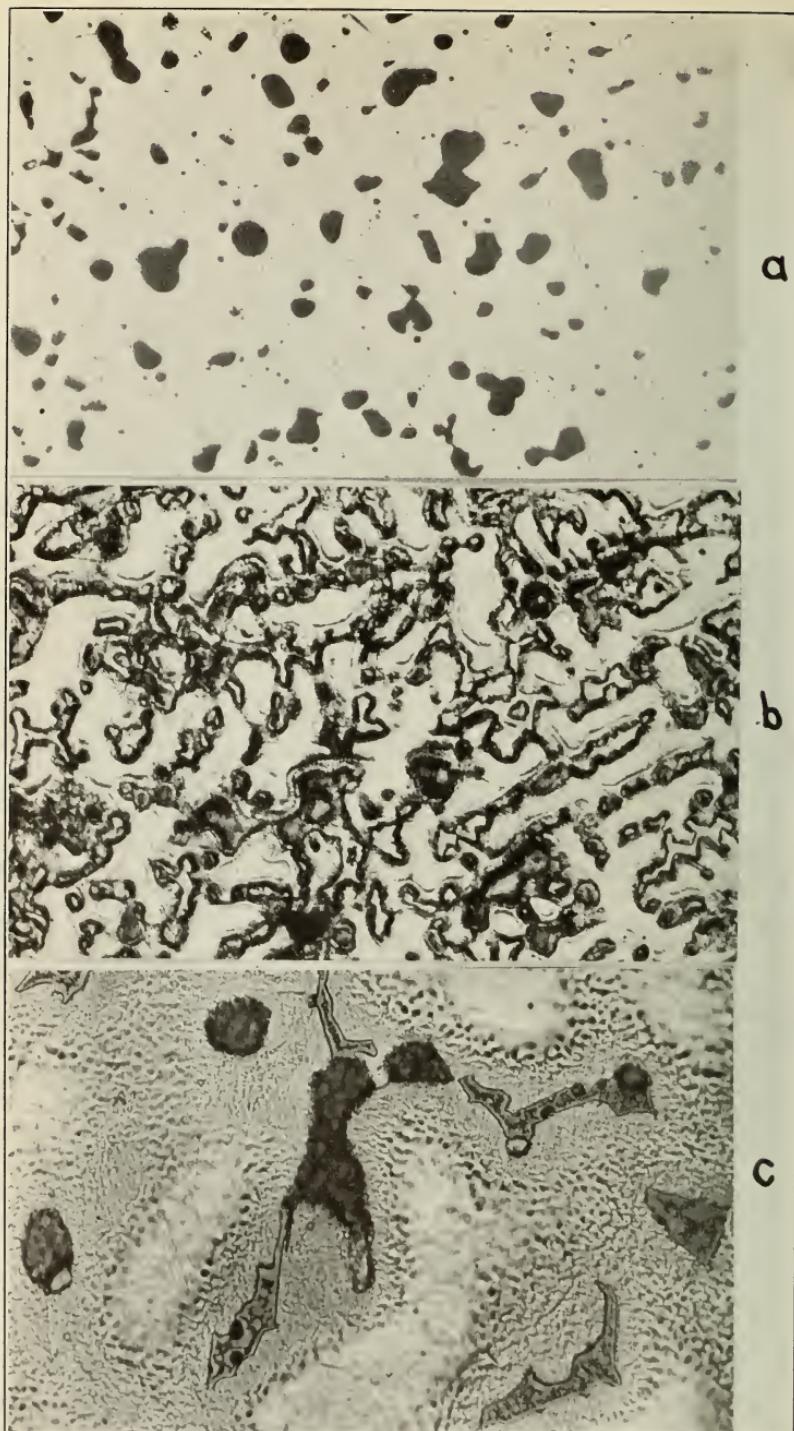


FIGURE 13.—Microstructure of 80-10-10 bronze with addition of 4 per cent zinc

Unetched,  $\times 100$ ; *b*, etched,  $\times 100$ ; *c*, etched,  $\times 500$ . Etchant 3 parts  $\text{NH}_4\text{OH}$  plus 1 part  $\text{H}_2\text{O}_2$ , followed by solution of  $\text{FeCl}_3$  in  $\text{HCl}$  (10 g  $\text{FeCl}_3$  plus 30 ml  $\text{HCl}$  plus 120 ml  $\text{H}_2\text{O}$ ).

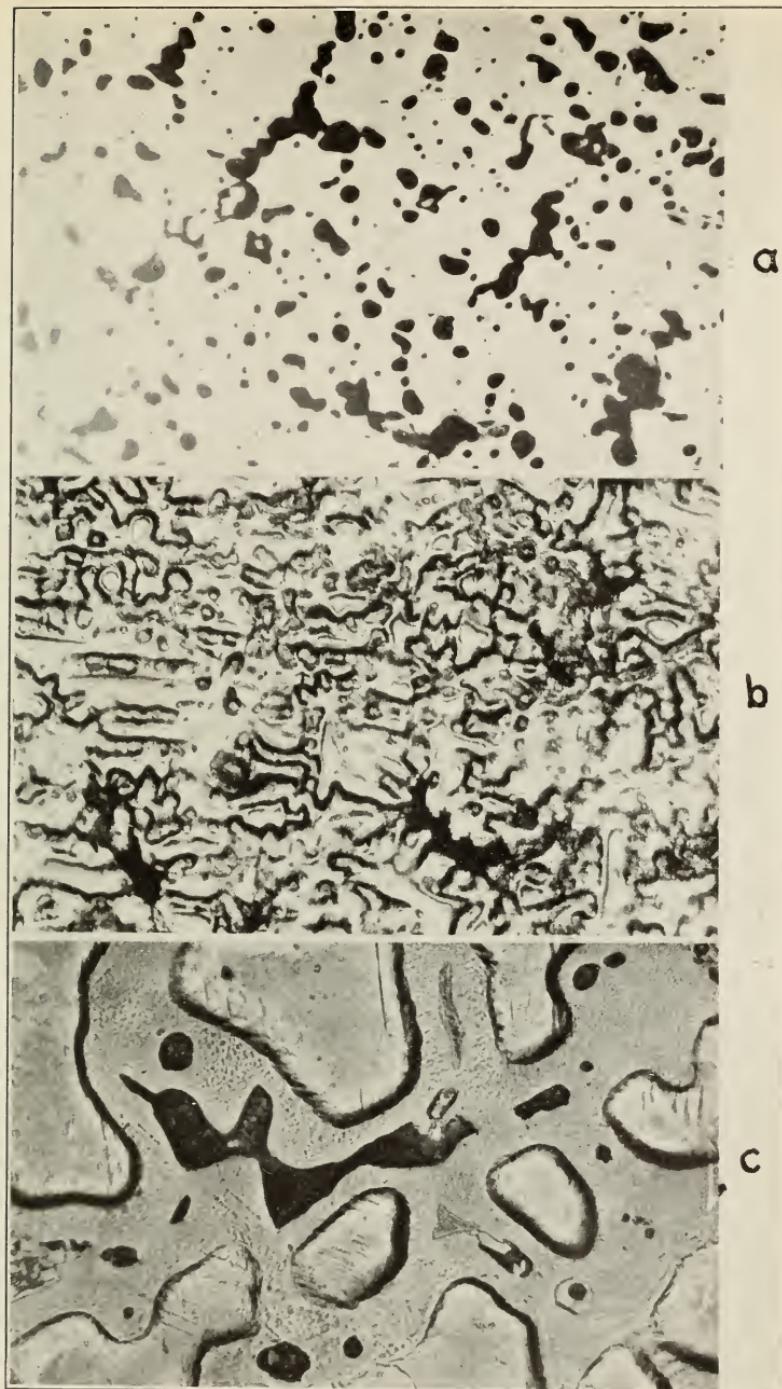


FIGURE 14.—Microstructure of 80-10-10 bronze with addition of 0.05 per cent phosphorus

a, Unetched,  $\times 100$ ; b, etched,  $\times 100$ ; c, etched,  $\times 500$ . Etchant 3 parts  $\text{NH}_4\text{OH}$  plus 1 part  $\text{H}_2\text{O}_2$ , followed by solution of  $\text{FeCl}_3$  in  $\text{HCl}$  (10 g  $\text{FeCl}_3$  plus 30 ml.  $\text{HCl}$  plus 120 ml  $\text{H}_2\text{O}$ ).

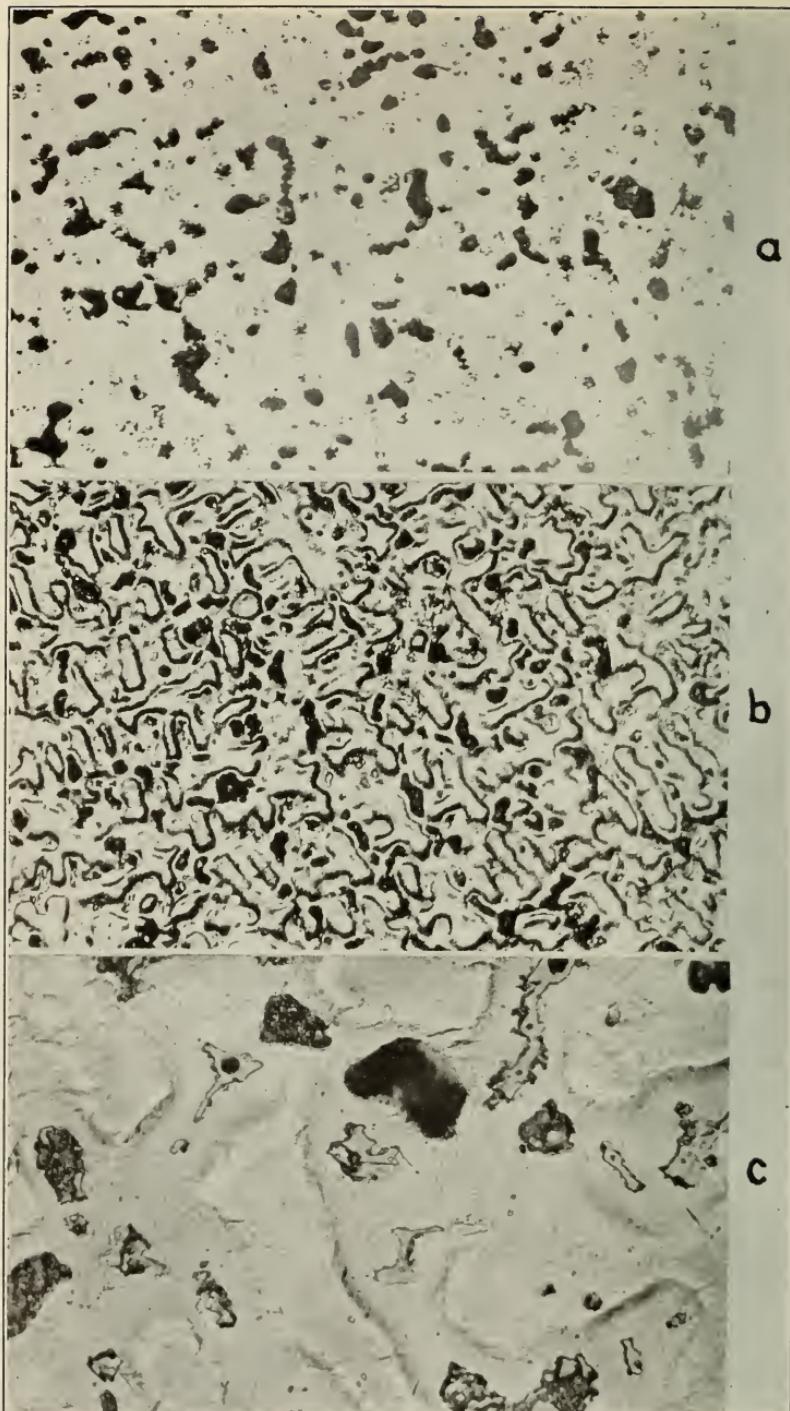


FIGURE 15.—Microstructure of 80-10-10 bronze with addition of 2 per cent nickel

a, Unetched,  $\times 100$ ; b, etched,  $\times 100$ ; c, etched,  $\times 500$ . Etchant 3 parts  $\text{NH}_4\text{OH}$  plus 1 part  $\text{H}_2\text{O}_2$ , followed by solution of  $\text{FeCl}_3$  in  $\text{HCl}$  (10 g  $\text{FeCl}_3$  plus 30 ml  $\text{HCl}$  plus 120 ml  $\text{H}_2\text{O}$ ).

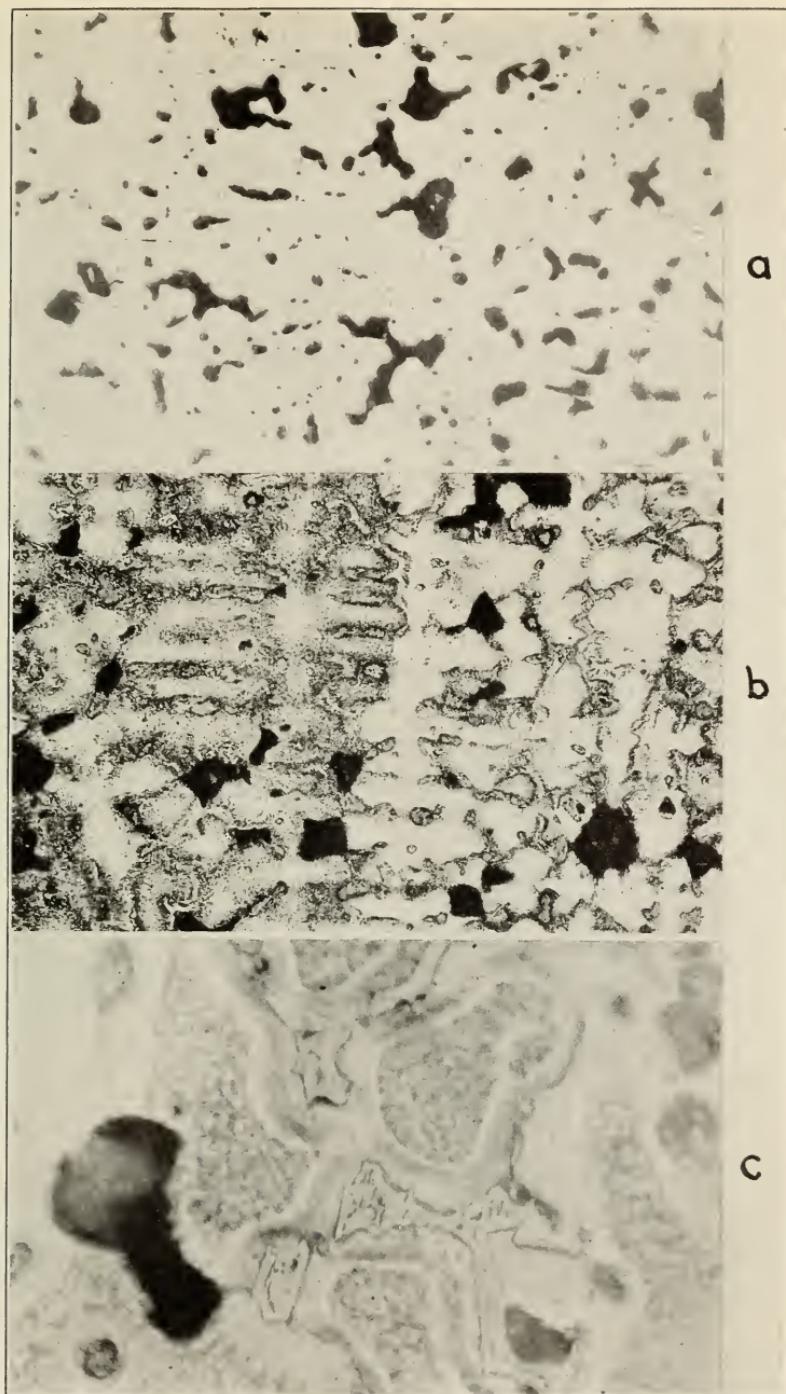


FIGURE 16.—Microstructure of 80-10-10 bronze with addition of 1 percent antimony

a, Unetched,  $\times 100$ ; b, etched,  $\times 100$ ; c, etched,  $\times 500$ . Etchant 3 parts  $\text{NH}_4\text{OH}$  plus 1 part  $\text{H}_2\text{O}_2$ , followed by solution of  $\text{FeCl}_3$  in  $\text{HCl}$  (10 g  $\text{FeCl}_3$  plus 30 ml  $\text{HCl}$  plus 120 ml  $\text{H}_2\text{O}$ ).



In some respects the results previously reported confirm those of Clamer,<sup>23</sup> who found that the addition of zinc to leaded bronzes hardened the alloys and increased the wear rate, but he concluded that the alloys having approximately 5 per cent tin, up to 20 per cent lead, and up to 5 per cent zinc should be entirely satisfactory for all classes of car-journal bearings.

#### (b) EFFECT OF 0.05 PER CENT PHOSPHORUS

Phosphorus is frequently added to deoxidize bronze and is generally added as phosphor-copper, although stick phosphorus is sometimes used. Phosphor bronze occasionally contains as much as 1 per cent phosphorus. Bronzes containing about 0.7 per cent phosphorus have been reported to have desirable mechanical properties by Philip<sup>24</sup> and others.

(1) *Structure.*—The addition of 0.05 per cent phosphorus to the base alloy of 80 per cent copper, 10 per cent tin, and 10 per cent lead appears to minimize the segregation of lead. (Figs. 12 (a) and 14 (a).) The grain size of the alloys containing phosphorus is finer than with the alloys without 0.05 per cent phosphorus. (Figs. 12 (b) and 14 (b).) This finer grain size may be largely responsible for the increased Brinell hardness and increased resistance to wear which was found for these alloys.

(2) *Wear resistance.*—In general, the addition of 0.05 per cent phosphorus was found to increase slightly the wear resistance, but not appreciably to affect the frictional force. Most of the alloys containing phosphorus showed a higher wear resistance than the base alloy at room temperature and at 350° F. (175° C.). However, alloy No. 10, basically 96 per cent copper, 2 per cent tin, and 2 per cent lead, showed the addition of phosphorus to be deleterious at both temperatures.

(3) *Repeated pounding.*—All of the alloys tested showed a consistent and appreciable effect of phosphorus on the resistance to pounding. At room temperature this effect was to increase the resistance to deformation, while at 350° F. (175° C.) there was little effect and at 600° F. (315° C.) there was a reduction in the resistance to deformation.

(4) *Resistance to impact.*—The addition of 0.05 per cent phosphorus had no marked effect on the notch toughness at either room temperature or 350° F. (175° C.). At 600° F. (315° C.) there was a tendency toward a slight increase in toughness.

(5) *Brinell hardness.*—Of the 8 alloys, with and without phosphorus, which were tested, 6 showed a slightly increased hardness due to the phosphorus addition, while for 2 the opposite was true. The magnitude of the effects found was not great, so it may be said that the phosphorus addition has little effect on the Brinell hardness, although the tendency seems to be toward an increase in hardness.

#### (c) EFFECT OF 2 PER CENT NICKEL

The results from the tests with bronzes which contained nickel were somewhat analogous with those of Corse,<sup>25</sup> who has reported that the tensile strength and elongation of 80-10-10 bronze is improved by the

<sup>23</sup> G. H. Clamer, Effect of Changes in the Composition of Alloys Used by the American Railways for Car Journal Bearings, *Trans. Am. Inst. Metals*, 9, p. 241; 1915.

<sup>24</sup> A. Philip, *J. Inst. Metals*, 1, No. 1, p. 174; 1909.

<sup>25</sup> W. M. Corse, Nickel in Brass and White Metals, *Met. Ind. (N. Y.)*, 22, p. 234; 1924.

addition of 1 per cent nickel. He has also stated that nickel additions also increase the rate of cooling and thereby reduce to a minimum the tendency toward lead segregation.

(1) *Structure.*—The alloys containing nickel (2 per cent) showed a finer distribution, less segregation of the lead, and also a finer-grain size than the comparison alloys containing no nickel. (Figs. 12 (a) and (b) and 15 (a) and (b).) It should be noted that the eutectoid constituent of the nickel alloy was comparatively free from alpha (fig. 15 (c)) and occurred frequently in direct contact with lead particles. This may account in part for the higher frictional forces and the decrease in wear resistance.

(2) *Wear resistance.*—All alloys containing 2 per cent nickel with the exception of No. 143, having a base composition of 85 per cent copper and 15 per cent tin, showed increased wear rates at room temperature. At 350° F. (175° C.) alloys Nos. 27 and 96 containing 80 copper, 10 tin, and 10 lead, and 88 copper, 10 tin, and 2 lead, respectively, gave results indicating a slightly beneficial effect of nickel. In general, the addition of 2 per cent nickel increased the wear rate of the alloys and slightly increased the frictional force as measured by the torque indicator.

(3) *Repeated pounding.*—A noteworthy advantage gained by the addition of 2 per cent nickel is apparent from the results of the pounding tests at room temperature. With the exception of those alloys very low in tin, Nos. 10 and 133, the addition of 2 per cent nickel increased the resistance to deformation of the alloys about 300 per cent. At 350° F. (175° C.) the beneficial effect of nickel was not as apparent as at room temperature, while at 600° F. (315° C.) there was no beneficial effect.

(4) *Resistance to impact.*—In the alloys containing low amounts of lead, Nos. 10, 96, and 143, the addition of 2 per cent nickel increased the resistance to impact at the three test temperatures; however, there was a decrease with alloy No. 143 at the test temperature of 600° F. (315° C.). However, with alloys containing over 2 per cent lead, there was, in general, a slight decrease in toughness.

(5) *Brinell hardness.*—The addition of 2 per cent nickel produced no marked effect on the hardness of the alloys studied, although there appeared to be a slight tendency toward an increase in hardness.

#### (d) EFFECT OF 1 PER CENT ANTIMONY

Antimony is nearly always considered an undesirable impurity in bronze. It has been stated, however, by Rolfe <sup>26</sup> that antimony frequently occurs in gun metal, sometimes so high as 1 per cent, and that gun-metal castings containing from 0.5 to 1 per cent antimony do not show any marked falling off in the mechanical properties. In a later publication, however, the same author <sup>27</sup> has stated that the effect of higher amounts of antimony is to increase progressively the hardness and brittleness and cause a progressive falling away in the strength and ductility. No difference in soundness or microstructure was reported.

(1) *Structure.*—In the alloys studied the addition of 1 per cent antimony to the base alloy of 80 per cent copper, 10 per cent tin, and

<sup>26</sup> R. T. Rolfe, Note on the Effect of Arsenic, Antimony, and Lead on 88-10-2 Gun Metal, *J. Inst. Met.*, **20**, p. 263; 1918.

<sup>27</sup> R. T. Rolfe, The Effect of Increasing Proportions of Antimony and Arsenic, Respectively, upon the Properties of Admiralty Gun Metal, *J. Inst. Met.*, **24**, p. 233; 1920.

10 per cent lead appeared to increase the segregation of lead. (Figs. 12 (a) and 16 (a).) The addition of antimony did not appear to affect the general grain size of the alloy. It is probable that the antimony is largely alloyed with the lead and results in a lower wear resistance as compared with the base alloy without antimony. (Figs. 12 (b) and (c) and 16 (b) and (c).)

(2) *Wear resistance.*—Although the addition of 1 per cent antimony in most instances increased the wear resistance of the alloys studied, it also increased the friction. At room temperature, the indicated friction of the alloys containing antimony was considerably higher than of those without antimony. This effect was not so noticeable at 350° F. (175° C.) as at room temperature.

(3) *Resistance to repeated pounding.*—There was a beneficial effect produced by 1 per cent antimony as regards the resistance to pounding. Increases as high as 300 per cent were noted at room temperature, while at 350° F. (175° C.) and 600° F. (315° C.) the advantage gained by adding antimony was still apparent.

(4) *Resistance to impact.*—Probably the most definite effect of antimony was to decrease the resistance to impact of copper-tin-lead alloys. In most of the alloys studied at the three test temperatures the addition of 1 per cent antimony reduced the resistance to impact about 30 per cent.

(5) *Brinell hardness.*—The addition of 1 per cent antimony had little effect on the hardness of the alloys studied, although there seemed to be a tendency toward an increase.

## VI. SUMMARY

Copper-tin-lead-bearing bronzes, high in copper, have been studied by the application of various mechanical tests, such as Brinell hardness, resistance to impact, resistance to repeated pounding, and resistance to wear.

The effects of several additions, 4 per cent zinc, 0.05 per cent phosphorus, 2 per cent nickel and 1 per cent antimony have been studied by the application of the individual tests previously mentioned.

The results of the study of the effects of different additions on the properties of bearing bronzes are briefly summarized in Table 3.

TABLE 3.—*General effects of additions studied on properties of bronzes*

| Addition                  | Property                                                                                              |                                                                                               |                                                                                           |                                  |
|---------------------------|-------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|----------------------------------|
|                           | Wear resistance<br>(Amsler test)                                                                      | Resistance to<br>pounding                                                                     | Resistance to impact<br>(Izod)                                                            | Brinell hardness                 |
| 4 per cent zinc.          | No appreciable effect. Decreased with alloys of low lead and high tin. Frictional force not affected. | Increased at room temperature. No appreciable effect at 350° and 600° F.                      | Tendency to increase toughness at 70°, 350°, and 600° F.                                  | Slightly harder.                 |
| 0.05 per cent phosphorus. | Increased in most cases. Frictional force not affected.                                               | Increased at room temperature. Little effect at 350° F. Pronounced decrease at 600° F.        | No definite change.                                                                       | Tendency toward slight increase. |
| 2 per cent nickel.        | Decreased. Frictional force slightly increased.                                                       | Marked increase at room temperature less marked at 350° F. Decreased in many cases at 600° F. | Increased with low lead alloys. Decreased with alloys having appreciable amounts of lead. | No appreciable change.           |
| 1 per cent antimony.      | Increased in most cases. Frictional force increased at room temperature.                              | Increased at all temperatures.                                                                | Decreased about 30 per cent.                                                              | Slightly harder in most cases.   |

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